UC 20+28

LBL-12635 c.1
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

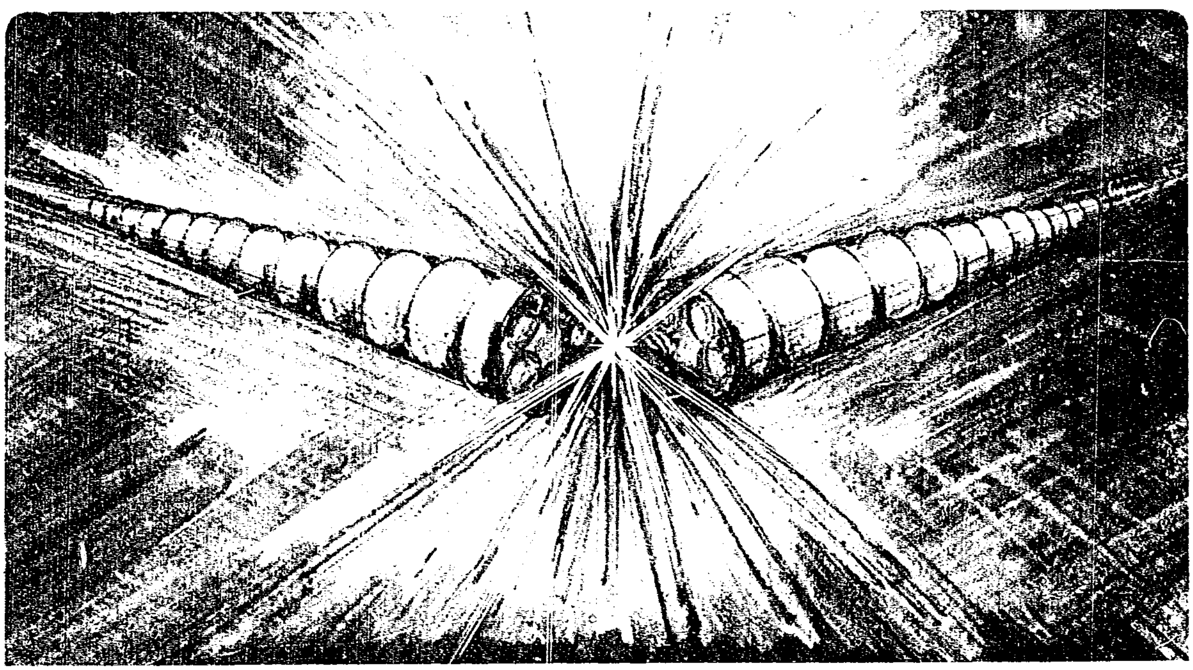
Accelerator & Fusion Research Division

Submitted to Nuclear Instruments and Methods

A METHOD FOR PRODUCING A HIGH QUALITY SOLENOIDAL FIELD

B. Feinberg, I.G. Brown, K. Halbach, and W.B. Kunkel

January 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

LBL-12635

A METHOD FOR PRODUCING A HIGH QUALITY SOLENOIDAL FIELD*

B. Feinberg, I. G. Brown, K. Halbach, W. B. Kunkel

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

January 1981

ABSTRACT

A relatively simple and inexpensive device is described which can be used to provide a highly homogeneous solenoidal magnetic field when the solenoid windings are inadequate. Design considerations and experimental measurements are presented. A field straightness of approximately 10^{-4} radians has been achieved.

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division, of the U. S. Department of Energy Under Contract No. W-7405-ENG-48.

I. Introduction

There exists a class of devices requiring a long, high current density electron beam. Typically an electron gun with high electrostatic area convergence [1] is used to yield a current density higher than the cathode emission limit. This beam is then injected into a rapidly rising solenoidal magnetic field to further increase the density [2]. A common application of this technique is the microwave traveling wave tube [3].

Some devices, however, require a very "high quality" magnetic field [4]. The axial field may be required to deviate from straightness by less than 10^{-3} radians. Expressed another way, the field line on axis would have a transverse deflection of less than 0.1 mm in a 10 cm axial length. The standard method of achieving this high quality field is to take great care in the winding of the solenoid. If high magnetic field strength is required, large cross-section conductor must be used for cooling normal coils, and this limits the winding tolerance. The standard solution is to use a superconducting solenoid with small diameter wire [4].

A method to ensure high field quality has been developed, using normal coils only. A structure consisting of a series of annular iron discs (i.e. flat rings) located within the magnet winding minimizes the transverse field components on the solenoid axis. This magnetic field "homogenizer" has enabled us to produce a field region which is straight to within 2×10^{-4} radians over an axial distance of 60 cm A description of the homogenizer, design considerations, field measurement technique, and the results obtained follows.

II. Background

A number of devices call for an axially propagating high current density electron beam. Microwave traveling wave tubes are perhaps the most common such aplication. [3] Another is the Electron Beam Ion Source, or EBIS, [4] which is a device for producing highly stripped heavy ions (e.g. Kr^{34+}, Xe^{48+}) [5] by containing the ions within a dense electron beam where successive electron impact ionization leads to high charge states. A high current density (up to 10^3 A/cm^2) is produced by injecting an electrostatically focused beam from an electron gun into a steeply rising magnetic field. The beam is compressed by the field and a high current density ensues. Matching of the beam to the magnetic field has been discussed by a number of authors. [6] For the compression to establish a uniform, high current density beam the field must be of very high quality; in particular the field line on axis must be very straight. This means that any off-axis transverse field components should be azimuthally symmetric. Empirically, various investigators have found that a field straightness better than 10^{-3} radians is required. [7]

We are constructing such an EBIS device at this laboratory. The solenoid design was dictated by the field strength required (up to 1 T) and the availability of suitable coils and power supplies at the laboratory. Three coils in series, with iron polepieces at either end, make up the solenoid. Each coil is 40 cm ID, 71 cm OD, and 15 cm thick, wound with 144 turns of 1.3 cm square cross-section copper tubing. The coils are spaced 9 cm apart. A peak field of 1 T is produced with a current of 1.4 kA provided by a D.C. motor generator. The required field quality is produced by the installation of the magnetic field homogenizer.

III. Design Consideration

The homogenizer acts to smooth out any asymmetric transverse magnetic field components. It consists of a series of annular iron rings. A schematic of the solenoid with the homogenizer in place is shown in Fig. 1, and a photograph of the homogenizer is shown in Fig. 2. Each iron ring forms a magnetic equipotential surface as long as the iron is not saturated. Any azimuthal asymmetries in the field due to errors in the solenoid windings are smoothed out by the iron and do not appear in the region inside the iron rings. The problem of field straightness therefore reduces to one of alignment of the iron rings, a much easier task than the alignment of many large copper windings which are under considerable stress.

To assess the necessary ring thickness, a, assume that one coil is displaced from the axis by Δr as shown in Fig. 3. The non-axisymmetric component of flux due to the displacement enters the iron near $\phi = 0$, and leaves the iron near $\phi = \pi$. The additional flux entering and leaving the iron due to the displacement is therefore proportional to $\cos\phi$, and the maximum flux in the ring is proportional to $\int_0^{\pi/2} \cos\phi d\phi$. Let the current density in the coil be j Amp/m^2.

A small radial displacement of the coil can be represented by a pair of current sheets of opposite signs on the inside and outside boundaries of the coil, and varying like $\cos\phi$. Figure 4 shows these current sheets labeled C and D. The amplitude of this non-axisymmetric current due to the displacement Δr is given by

$$I' = j\Delta r(\text{Amp/m}) = H_c \;.$$

This pair of current sheets is equivalent to a pair of magnetic charge sheets at the two ends of the coil, shown in Fig. 4 as sheets A and B. The field perturbation due to the radial displacement can therefore be calculated by analyzing these magnetic charge sheets. The charge distribution is

$$\mu_o \, H_c \cos \phi \;.$$

Looking at a differential area,

$$d\,\Phi = (\mu_o \, H_c \cos\phi \; \pi(R_2^2 - R_1^2)/2\pi)d\phi$$

$$= \mu_o \, H_c \, \bar{R}\Delta R \cos\phi \; d\phi$$

Therefore the maximum flux in an annular ring is given by

$$\Phi = \eta \int_0^{\pi/2} \mu_0 j \Delta r \cos\phi d\phi \, \overline{R} \Delta R$$

$$= \eta \mu_0 j \Delta r \, \overline{R} \Delta R,$$

where η is the fraction of the flux which enters a particular ring. Let L_c be the axial length of the coil, and L_1 be the distance between coil centers.

Then

$$I = j \, \Delta R \, L_c \approx H_0 \, L_1 ,$$

where H_0 is the field on the solenoid axis.

Therefore

$$\Phi = \eta \Delta r B_0 (L_1/L_c) \overline{R}.$$

If the maximum field allowed in the ring to avoid saturation is B_1,

$$\Phi \leq B_1 ab$$

where a is the ring thickness and b is the radial extent, as shown in Fig. 3.

Therefore

$$a \geq \eta \frac{B_0}{B_1} \frac{L_1}{L_c} \frac{\overline{R}}{b} \Delta r \qquad (1)$$

In a similar manner, tilt can be represented by $\Delta r = R\alpha$, where α is the maximum angular displacement of the coil.

Note that B_1 does not include the symmetric field which passes through each ring in the axial direction. This field can be included by letting $(B_1{}^2 + B_0{}^2)^{\frac{1}{2}}$ be less than the maximum field to avoid saturation. There are two other effects which should be mentioned. The axial field between the rings is increased due to the presence of the rings. This effect is small if $a \ll \lambda$. Additional flux also enters the rings through the inner and outer radii, but this flux is small if $a \ll b$.

To continue with the design, one must determine η. The error due to a radial displacement can be represented by the 2 equal magnetic charge sheets of opposite signs labeled A and B in Figure 4. Symmetry ensures the additional flux to ring 3 is zero. The flux to ring 2 is given approximately as 1/2 of the flux from A, and 1/4 of the flux from B. An approximate division of flux is therefore

$$\Phi_1 = \frac{1}{4}\Phi_A, \quad \Phi_2 = \frac{1}{2}\Phi_A + \frac{1}{4}\Phi_B, \quad \Phi_3 = 0, \quad \Phi_4 = \frac{1}{4}\Phi_A + \frac{1}{2}\Phi_B$$

Let $$\Phi_A = -\Phi_B = \Phi, \text{ and } \eta_i = \left|\Phi_i / \Phi\right|$$

Therefore $$\eta_1 = \eta_2 = \eta_4 = \frac{1}{4}, \quad \eta_3 = 0$$

A representative maximum value for η is $\eta \approx 1/4$. For tilt one obtains charge sheets C and D, and by a similar analysis the maximum value of η is $\eta \approx 1/4$.

A final parameter yet to be determined is b, the radial extent of the rings. From figure 4 it is clear that one desires the rings to be close to the coils in order to intercept the most flux possible, and therefore the outer radius will be determined by space considerations. For the ideal symmetric case the rings produce a ripple in the field magnitude on the axis and do not affect the straightness. The allowable ripple will determine r_1, the inner radius of the rings. The perturbation on the axis due to a perturbation at r_1 is given by

$$\Delta H_z\ (r = o) = \Delta H_z\ (r_1)\ /\ I_o\ (kr_1)$$

where I_o is the modified Bessel function and $k = 2\pi/\lambda$ where λ is the axial symmetry distance as shown on Fig. 3.

If

$$kr_1 >> 1$$

and

$$\Delta H_z(r_1) \sim \frac{a}{\lambda} H_o$$

then

$$\frac{\Delta H_z(0)}{H_o} \sim \frac{a}{\lambda} 2\pi \left(\frac{r_1}{\lambda}\right)^{\frac{1}{2}} \exp(-2\pi r_1/\lambda) \left\{1+ \frac{1}{16\pi r_1/\lambda}\right\}^{-1}$$

For most practical cases, the ripple turns out to be very small, and b can be made as large as is practical consistent with space considerations.

Therefore Eq. 1 can be used to determine the ring thickness, now that η and b are known. If one lets $B_o = 1$ T and $B_1 = 1$ T to avoid saturation, for a = 1.3 cm, b = 5.5 cm, L_1 = 24.4 cm, L_c = 16.8 cm, $\bar{R}$ = 27.9 cm, and $\eta = 1/4$ one finds Δr = 0.7 cm. Therefore a displacement of 0.7 cm in the radial position of a coil will not saturate the homogenizer. Likewise, a tilt of approximately 25 mrad is acceptable.

IV. Configuration and Measurements

The homogenizer, shown in Fig. 2, is made from well annealed, type 1018, low carbon steel. The ring dimensions are 37.6 cm OD, 26.7 cm ID, and 1.3 cm thick. Repeated machining and annealing was performed to ensure a homogeneous permeability. Three spaced rings are located under each coil, machined to a tolerance of 25 μm. Cylindrical aluminum spacers and type 310 stainless steel rods provide a rigid clamping structure with low magnetic susceptibility. The rings in the finished assembly are parallel and coaxial to within 25 μm.

The field quality has been measured, using the technique of Nishihara and Terada [8]. The resolution of our magnetic (Hall effect) probe assembly is such that a deviation from straightness of approximately 10^{-4} radians, or an axial field line deflection of approximately 10 μm in a length of 10 cm can be measured. Some results of these measurements are shown in figures 5 and 6. The projection in the transverse plane of a field line near the axis is shown for various axial positions given by the labeled points. Figure 5a shows the field without the homogenizer, and figure 6a shows the field with the homogenizer. A constant vector can be subtracted from these trajectories compensating for any misalignment of the axis of the probe assembly from the solenoidal axis, and therefore permitting a clearer comparison. Figures 5b and 6b show these projections, without and with the homogenizer, respectively. With the homogenizer, the field line is straight to ± 40 μm over an axial distance of 60 cm.

Further verification of the straightness of the axis is shown in Fig. 7. An electron gun is located outside one end of the solenoid, and a tungsten sheet 25 μm inch thick is moved along the axis. A telescope is used to measure the location in the transverse plane of the spot on the tungsten heated by the (pulsed) electron beam. Upon removing the constant vector, figure 7 shows the beam trajectory to be straight within ± 50 μm (the limit of resolution) over an axial distance of 55 cm. The field axis was adjusted to achieve these results by slight shifting of the homogenizer. Through judicious adjustments of the tilt and transverse position of the homogenizer, a field line passing through the center of both pole pieces and normal to the first polepiece is obtained.

V. Conclusion

A simple piece of hardware has been described which can be used to produce a highly homogeneous magnetic field when the solenoidal windings are inadequate. The field straightness produced in this case is approximately 10^{-4} radians.

VI. Acknowledgement

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

References

[1] J. R. Pierce, Theory and Design of Electron Beams, D. Van Nostrand, NY (1954); R. D. Frost, O.T. Puri, H. R. Johnson, Proc. IRE 50, 1800 (1962).

[2] G. R. Brewer in Focusing of High-Density Electron Beams, V. 2, Edited by Septier, Acadmic Press, NY (1967), p. 73; K. Amboss, IEEE Trans. on Electron Devices ED-16, 897 (1969).

[3] G. R. Brewer, J. Appl. Phys. 28, 7 (1957).

[4] E. D. Donets, IEEE Trans. on Nuclear Science NS-23, 897 (1976); J. Arianer, C. Goldstein, IEEE Trans. on Nuclear Science NS-23, 979 (1976).

[5] J. Arianer, A. Cabrespine, C. Goldstein, IEEE Trans. Nuclear Science NS-26, 3713 (1979); E. D. Donets, V. P. Ovsyannikov, V. G. Dudnikov, Communication of Joint Institute Nuclear Research, P7-12905, Dubna, USSR (1979).

[6] V. Bevc, J. L. Palmer, C. Susskind, J. Brit. IRE 18, 696 (1958); C. R. Moster, J. P. Molnar, Bell Labs Memorandum MM51-2940-1, MM51-2960-1 (1951); See also Reference 2.

[7] J. Arianer, Private Communication.

[8] H. Nishihara, M. Terada, J. Appl. Phys. 39, 4573 (1968); J. Appl. Phys. 41, 3322 (1970).

Figure Captions

Figure 1. Schematic of the solenoid, including the coils, the iron polepieces, and the magnetic homogenizer rings.

Figure 2. Photograph of the magnetic homogenizer. The soft iron rings are supported by aluminum spacers, and held together with non-permeable stainless steel rods.

Figure 3. Two views of the coil and homogenizer configuration, showing the labels used in the equations, the assymetrical displacement of one coil by Δr, and the flux distribution in one iron ring of the homogenizer.

Figure 4. An idealized schematic of a coil and the nearby homogenizer rings.

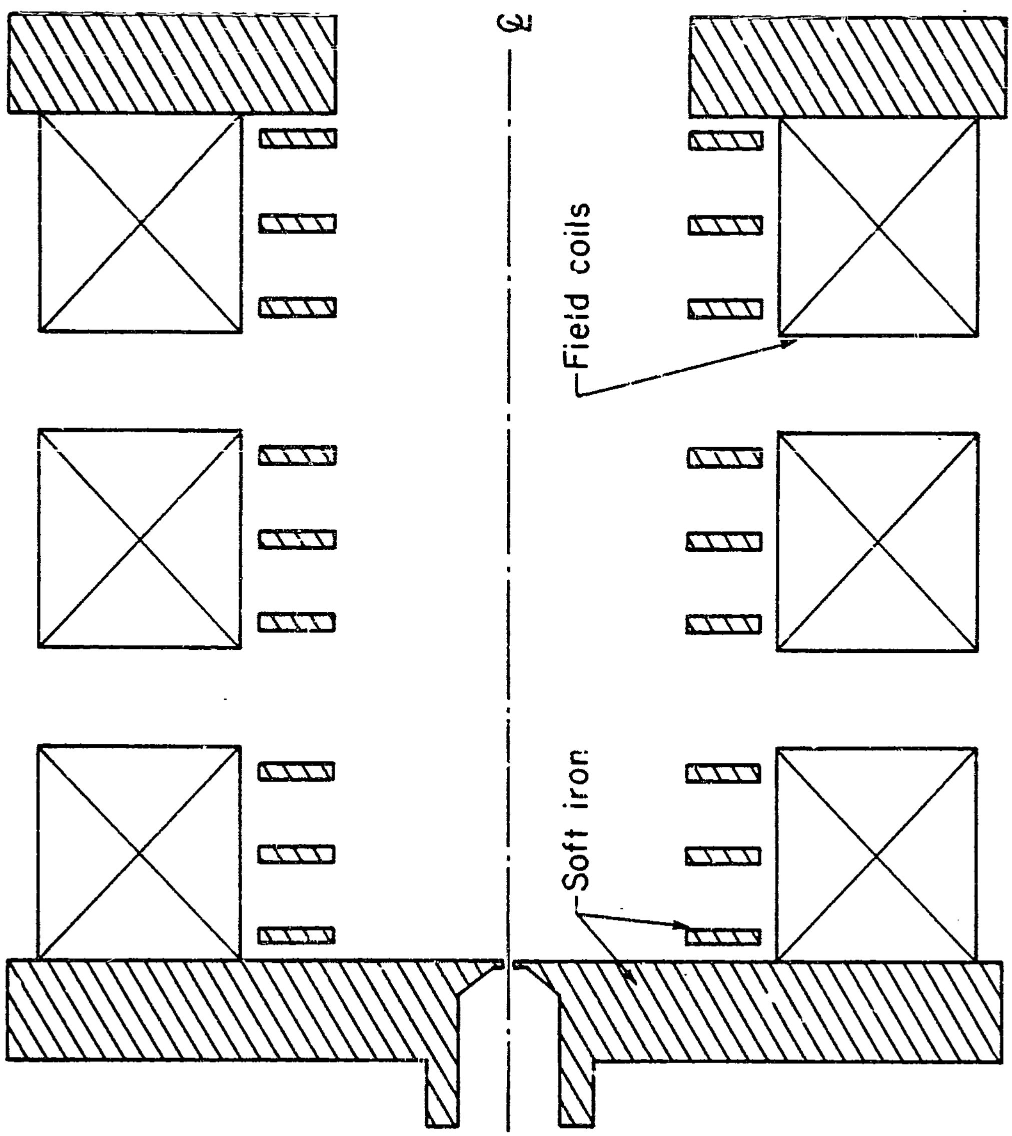
Figure 5. Polar projection of the magnetic field axis before using the magnetic homogenizer, showing the radial deviation in mm for various axial locations 5 cm apart.

a) Raw projection
b) Projection subtracting a constant vector to compensate for misalignment of the magnetic probe axis.

Figure 6. Polar projection of the magnetic field axis with the magnetic homogenizer in place, showing the radial deviation in mm for various axial locations 5 cm apart.

a) Raw projection
b) Projection subtracting a constant vector to compensate for misalignment of the magnetic probe axis.

Figure 7. Polar projection of the electron beam trajectory, showing the radial deviation in mm for various axial locations 5 cm apart.

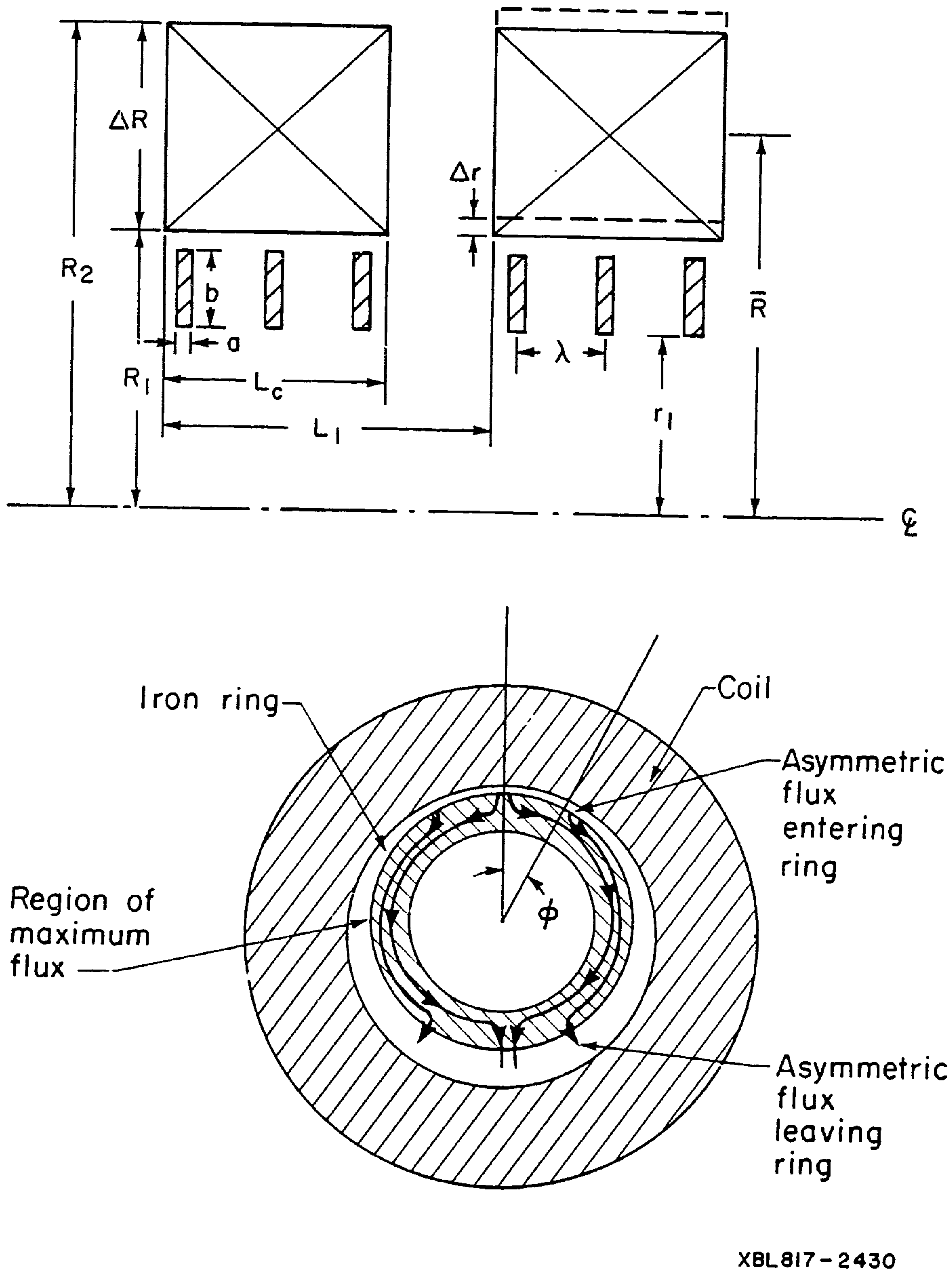


XBL 817-2431

FIG. 1

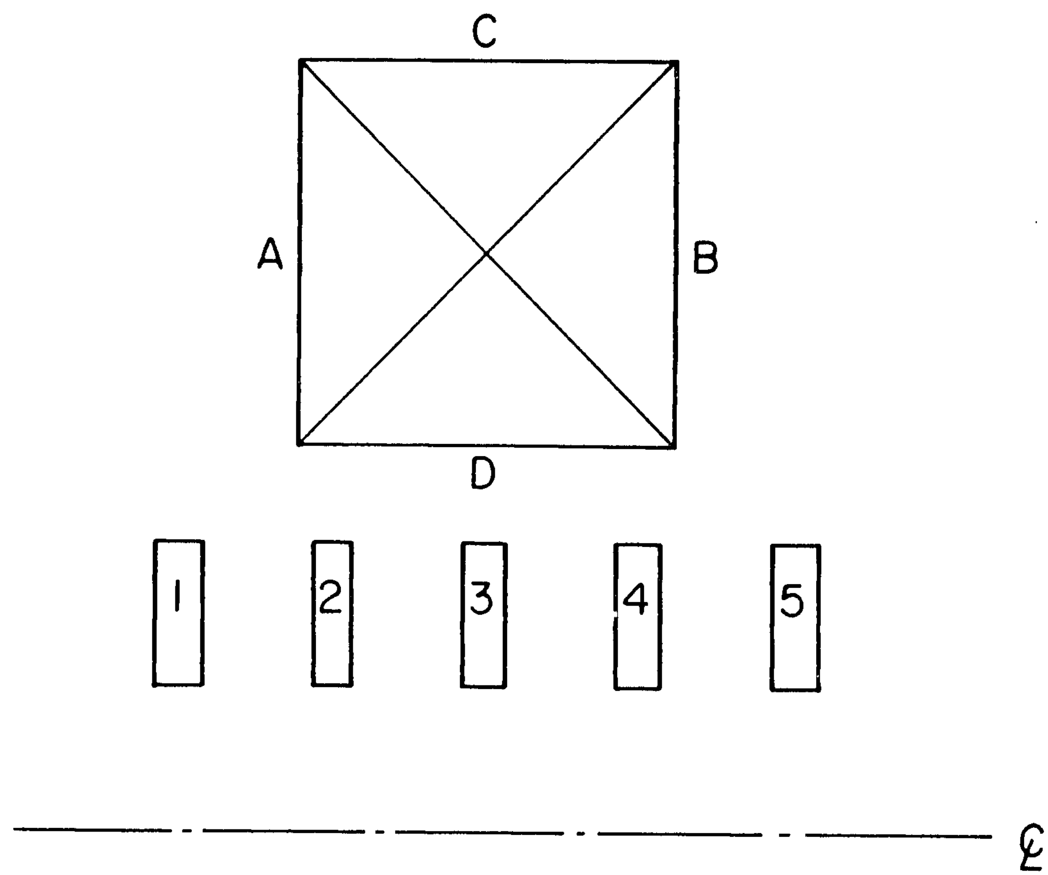
XBB 814-3959

FIG. 2



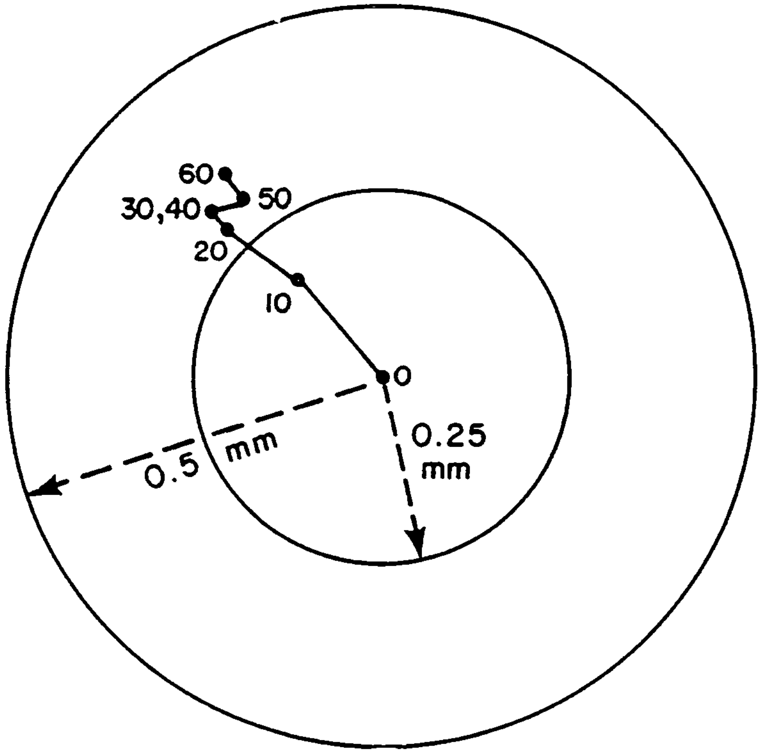
ΔR
R_2
b
a
R_1
L_c
L_1
Δr
λ
r_1
$\bar{R}$
℄
Iron ring
Coil
Asymmetric flux entering ring
Region of maximum flux
ϕ
Asymmetric flux leaving ring
XBL817-2430

FIG. 3



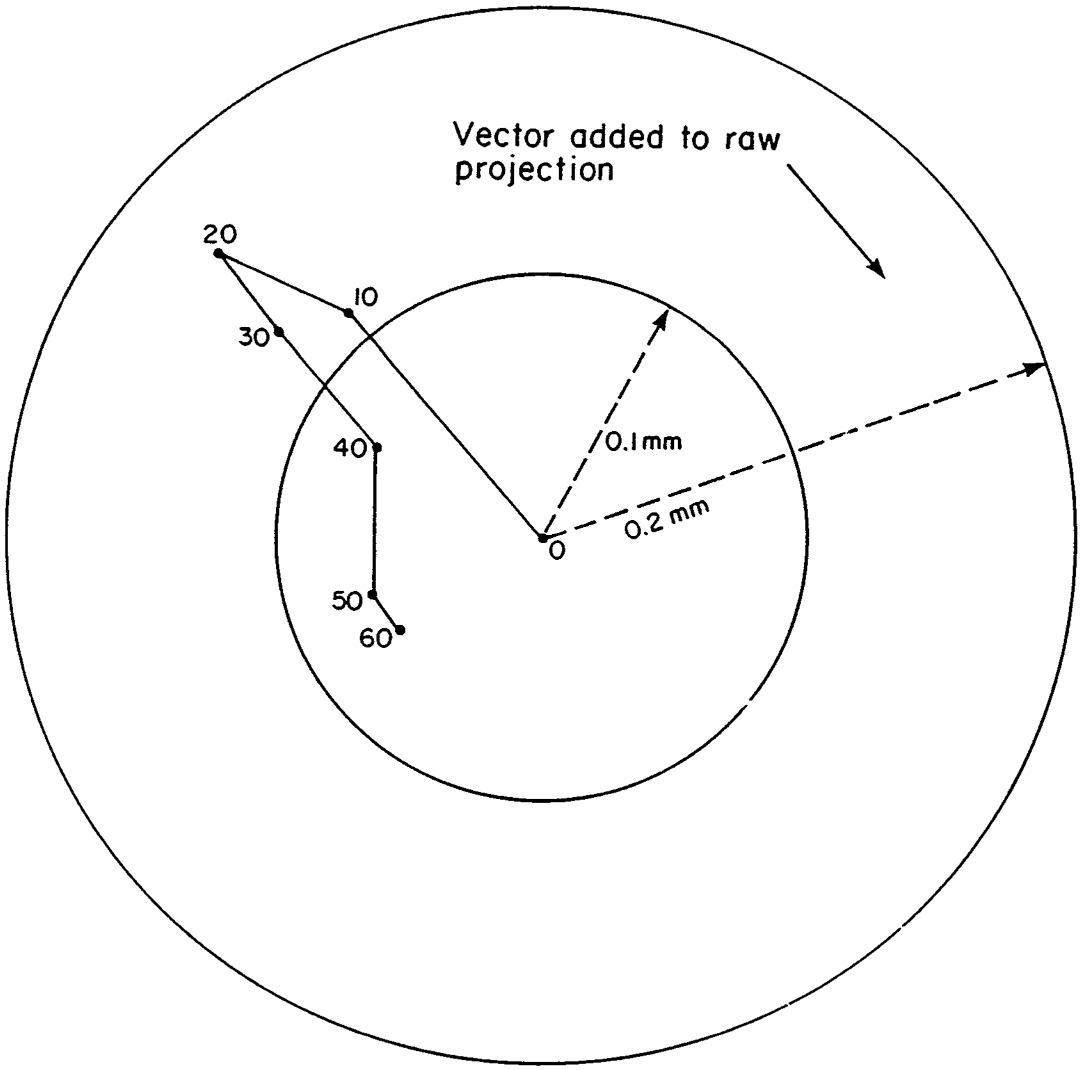
XBL 817-2433

FIG. 4



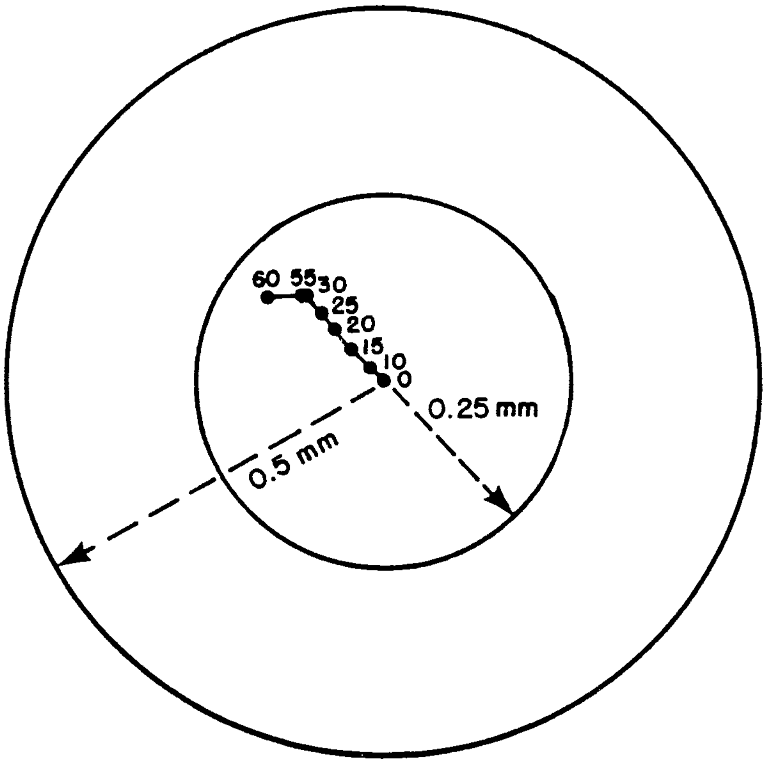
XBL 817-2432

FIG. 5 A



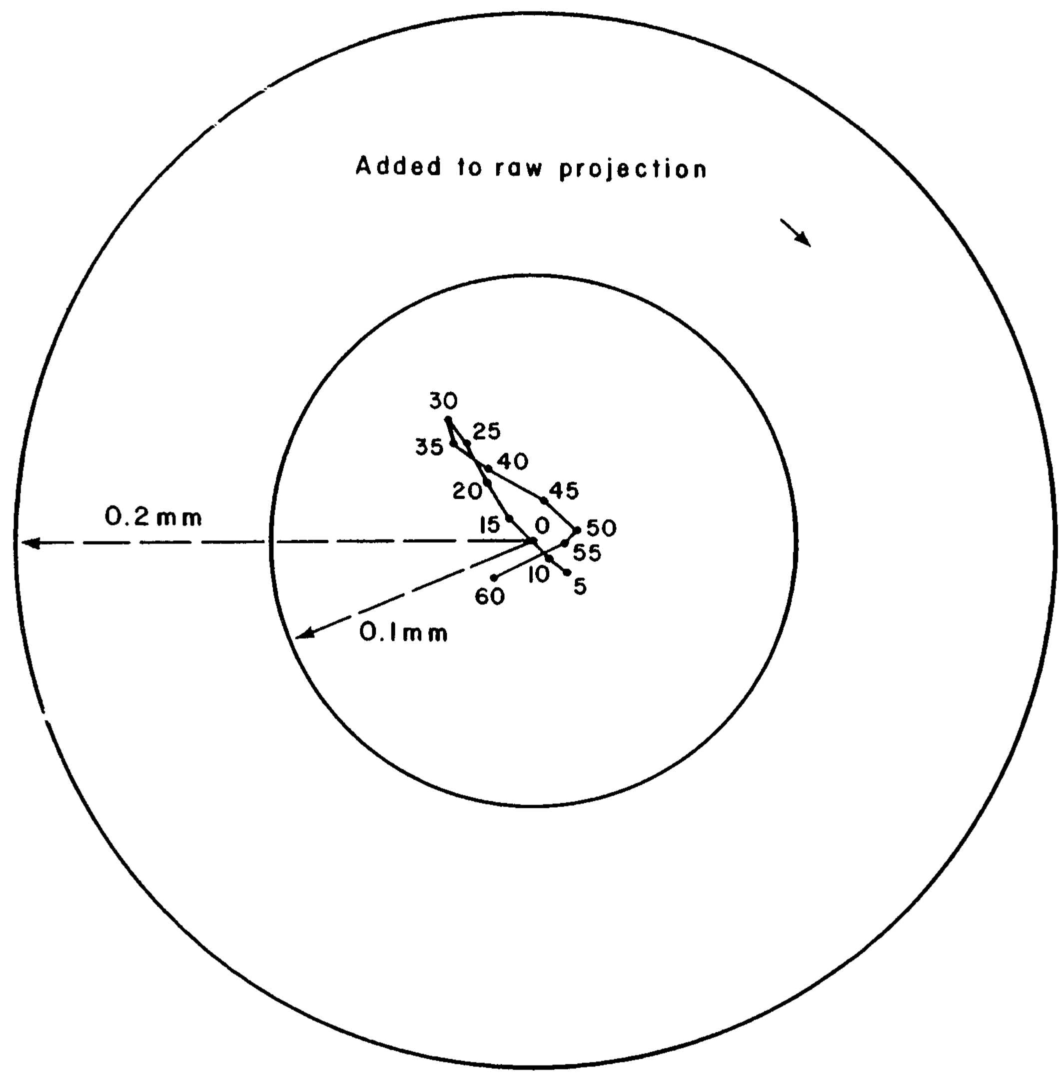
XBL 817-2434

FIG. 5 B



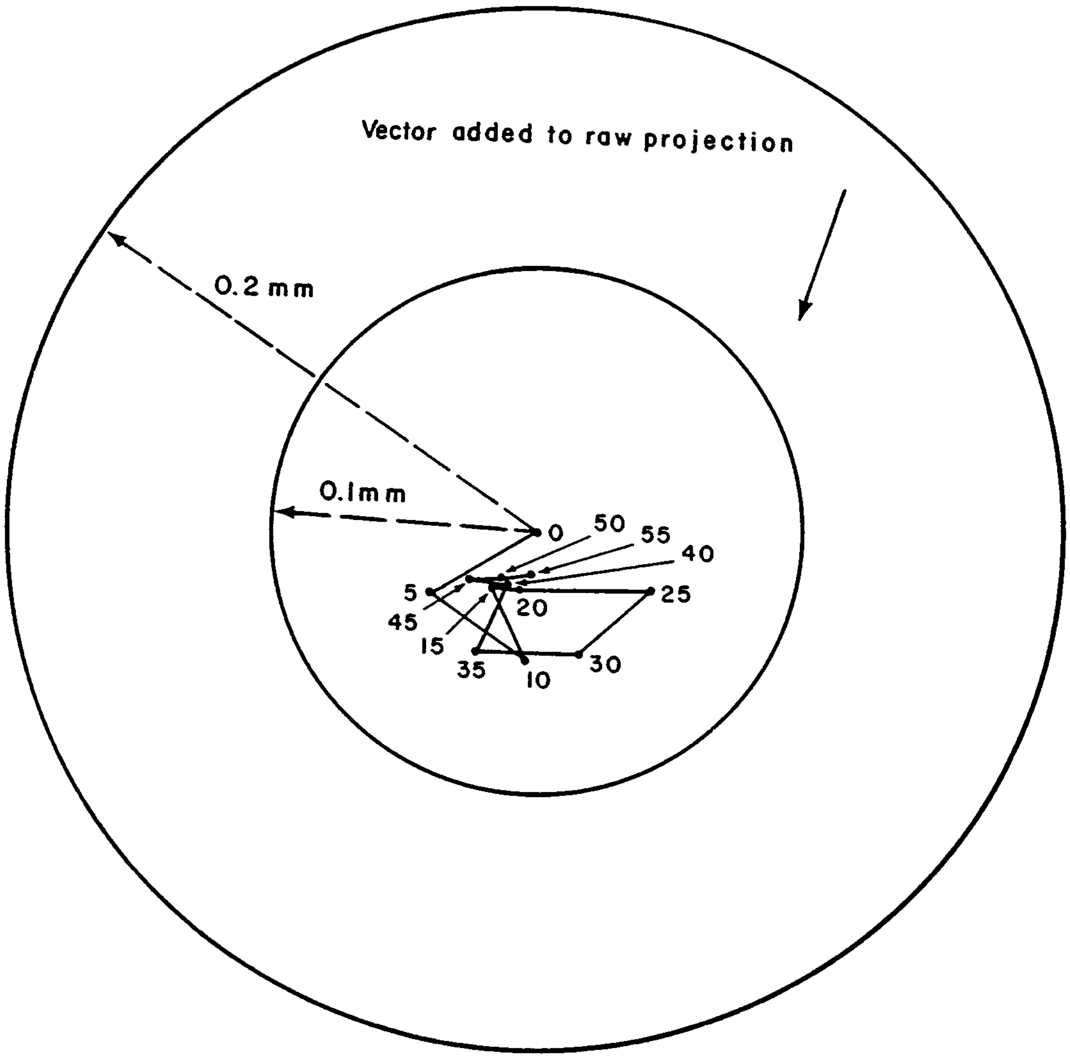
XBL817—2435

FIG. 6 A



XBL 814-759

FIG. 6 B



XBL 814-758

FIG. 7